Volume Title
*ASP Conference Series, Vol. **Volume Number***
Author

The Physical Basis of the $L_x \sim L_{bol}$ Empirical Law for O-star X-rays

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Abstract.
X-ray satellites since *Einstein* have empirically established that the X-ray luminosity from single O-stars scales linearly with bolometric luminosity, $L_x \sim 10^{-7} L_{bol}$. But straightforward forms of the most favored model, in which X-rays arise from instability-generated shocks embedded in the stellar wind, predict a steeper scaling, either with mass loss rate $L_x \sim \dot{M} \sim L_{bol}^{1.7}$ if the shocks are radiative, or with $L_x \sim \dot{M}^2 \sim L_{bol}^{3.4}$ if they are adiabatic. We present here a generalized formalism that bridges these radiative vs. adiabatic limits in terms of the ratio of the shock cooling length to the local radius. Noting that the thin-shell instability of radiative shocks should lead to extensive mixing of hot and cool material, we then propose that the associated softening and weakening of the X-ray emission can be parameterized by the cooling length ratio raised to a power m, the "mixing exponent." For physically reasonable values $m \approx 0.4$, this leads to an X-ray luminosity $L_x \sim \dot{M}^{0.6} \sim L_{bol}$ that matches the empirical scaling. We conclude by noting that such thin-shell mixing may also be important for X-rays from colliding wind binaries, and that future numerical simulation studies will be needed to test this thin-shell mixing *ansatz* for X-ray emission.

1. Introduction

Since the 1970's X-ray satellite missions like *Einstein*, *Rosat*, and most recently *Chandra* and *XMM-Newton* have found hot, luminous, O-type stars to be sources of soft ($\lesssim$ 1 keV) X-rays, with a roughly *linear* scaling between the X-ray luminosity and the stellar bolometric luminosity, $L_x \sim 10^{-7} L_{bol}$ (Güdel & Nazé 2009). In some systems with harder (a few keV) spectra and/or higher L_x, the observed X-rays have been associated with shock emission in colliding wind binary (CWB) systems, or with magnetically confined wind shocks (MCWS) (see reviews by Corcoran and Gagné). But in putatively single, non-magnetic O-stars, the most favored model is that the X-rays are emitted from Embedded Wind Shocks (EWS) that form from the strong, intrinsic instability (the "Line-Deshadowing Instability" or LDI) associated with the driving of these winds by line-scattering of the star's radiative flux (see review by Sundqvist).

This LDI can be simply viewed as causing some small ($\lesssim 10^{-3}$) fraction of the wind material to pass through an X-ray emitting EWS, suggesting then that the X-ray luminosity should scale with the wind mass loss rate, $L_x \sim \dot{M}$. But within the standard Castor et al. (1975, hereafter CAK) model for such winds, this mass loss rate increases

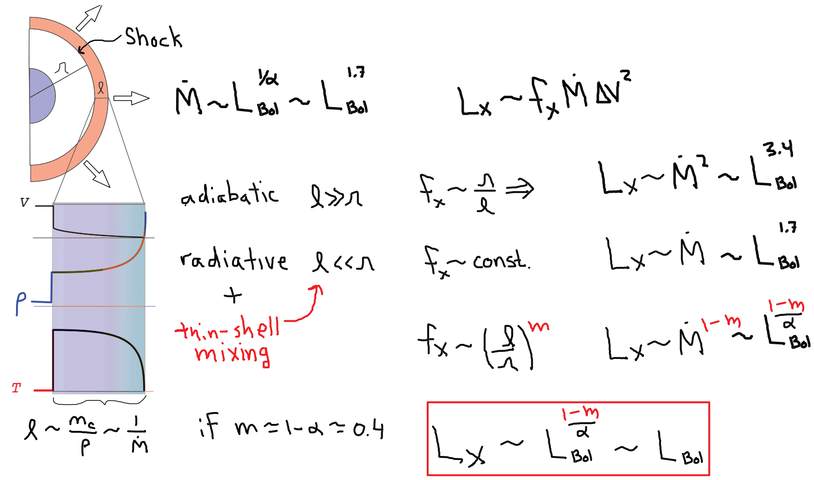

Figure 1. Illustration of cooling zone within a wind shock, showing associated scalings for X-ray luminosity L_x with mass loss rate $\dot{M}$ and bolometric luminosity L_{bol}, for adiabatic shocks with cooling length much larger than the local radius, $\ell \gg r$, or radiative shocks with $\ell \ll r$. Thin-shell mixing of such radiative shocks is posited to lead to a reduction of the X-ray emitting fraction that scales as a power-law of cooling length, $f_x \sim \ell^m$. For CAK wind index α, a mixing exponent $m = 1 - \alpha$ leads to the observationally inferred linear scaling of X-rays with bolometric luminosity, $L_x \sim L_{bol}$.

with luminosity[1] as $\dot{M} \sim L_{bol}^{1/\alpha} \sim L_{bol}^{1.7}$, where the latter scaling uses a typical CAK power index $\alpha \approx 0.6$. This then implies a *super-linear* scaling for X-ray to bolometric luminosity, $L_x \sim L_{bol}^{1.7}$, that is too steep to match the observed, near-linear law.

In fact, the above scaling effectively assumes the shocks are *radiative*, with a cooling length that is much smaller than the local radius, $\ell \ll r$. In the opposite limit $\ell \gg r$, applicable to lower-density winds for which shocks cool by *adiabatic* expansion, the shock emission scales with the X-ray *emission measure*, $EM \sim \int \rho^2 dV$, leading then to an even steeper scaling of X-ray vs. bolometric luminosity, $L_x \sim \dot{M}^2 \sim L_{bol}^{3.4}$.

Both these scalings ignore the effect of bound-free absorption of X-rays by the cool, unshocked material that represents the bulk of the stellar wind. Owocki & Cohen (1999, OC99) showed that, in an EWS model in which the X-ray emission fraction drops with radius, accounting for wind absorption can lead to an observed X-ray luminosity that scales linearly with L_{bol}. But while modern observations of spectrally resolved X-ray emission profiles by *Chandra* and *XMM-Newton* do indeed show the expected broadening from EWS, the relatively weak blue-red asymmetry indicates that such absorption effects are modest in even the densest winds (Cohen et al. 2010, 2011). Since many stars following the L_x-L_{bol} empirical law have weaker winds that are largely optically thin to X-rays, it now seems clear that absorption cannot explain this broad L_x scaling.

[1]For simplicity, we ignore here secondary scalings, e.g. of luminosity with mass, or wind speed with mass and radius.

The analysis here examines instead the role of radiative cooling, and associated thin-shell instabilities, in mixing shock-heated material with cooler gas, and thereby reducing and softening the overall X-ray emission. As summarized in figure 1, for a simple parameterization that this mixing reduction scales with a power (the "mixing exponent" m) of the cooling length, ℓ^m, we find that the linear L_x-L_{bol} law can be reproduced by assuming $m \approx 0.4$. To lay the basis for deriving this result in §3, the next section (§2) first introduces a simple bridging form for emission between the radiative and adiabatic shock limits.

2. Bridging Law for Adiabatic vs. Radiative Shock Emission

Building upon the LDI-generated EWS scenario that is reviewed in this volume by Sundqvist et al., let us model the associated local X-ray emissivity within the wind as

$$\eta_x = C\rho^2 f_v = C\rho^2 \frac{f_q}{1 + r/\ell}\,, \tag{1}$$

where ρ is the wind density, C is a constant that depends on the shock model and atomic physics, and f_v represents a volume filling factor for X-ray emission. While previous work (e.g., OC99) has often directly parameterized this factor as following some specified radial function (e.g. power-law), the second equality in eqn. (1) casts this in terms of a "bridging law" between the limits for radiative ($\ell \ll r$) and adiabatic ($\ell \gg r$) shocks, where f_q now represents some local "heating fraction", set by LDI-generated EWS. The cooling length itself scales as,

$$\ell = \frac{m_c}{\rho} \equiv \frac{1}{\kappa_c \rho}. \tag{2}$$

where the cooling mass column m_c depends on the energy of the EWS, and $\kappa_c = 1/m_c$ provides a convenient representation with units of opacity or mass-absorption coefficient, e.g. cm^2/g. In the simple model here, we assume that the shock energy is fixed, and thus that κ_c is spatially constant. From eqns. (18) and (22) of Antokhin et al. (2004), we find the numerical value

$$\kappa_c \approx 190\, E_{kev}^{-2}\, \mathrm{cm}^2/\mathrm{g}\,, \tag{3}$$

where E_{kev} is the shock energy in keV.

For X-rays emitted with photon energy comparable to the shock energy, the bound-free absorption opacity has roughly a similar inverse-square energy dependence, but with a numerical coefficient that is about a factor $\kappa_c/\kappa_{bf} \approx 8$ smaller. For a wind with mass loss rate $\dot{M}$ and flow speed V_∞, the transition from optically thick to thin X-ray emission can be characterized by the unit-optical-depth radius for bound-free absorption,

$$R_1 \equiv \frac{\kappa_{bf}\dot{M}}{4\pi V_\infty}\,. \tag{4}$$

In direct analogy, we can define a characteristic *adiabatic radius* for transition from radiative to adiabatic cooling of the associated wind shocks,

$$R_a \equiv \frac{\kappa_c \dot{M}}{4\pi V_\infty} \approx 140 R_\odot \frac{\dot{M}_{-6}}{E_{kev}^2 V_{1000}}\,, \tag{5}$$

where $\dot{M}_{-6} \equiv \dot{M}/10^{-6} M_{\odot}/\mathrm{yr}$ and $V_{1000} \equiv V_\infty/1000$ km/s. For even the densest winds, the X-ray emission onset $R_o \gtrsim R_1$, implying, as noted above, that wind absorption is at most a modest effect. But the stronger coefficient ($\kappa_c/\kappa_{bf} \approx 8$) for radiative cooling means that such winds generally have $R_a \gg R_o$, implying that most O-star EWS remain radiative well above the wind acceleration region where they are generated (Zhekov & Palla 2007).

3. Thin-Shell Instability and Shock Mixing

The inherent thinness of radiative shock cooling zones makes them subject to various thin-shell instabilities (Vishniac 1994). These can be expected to lead to an unknown, but potentially substantial, level of *mixing* between cool and hot material. Since cooler material radiates more efficiently, and in softer wavebands (toward the UV instead of X-rays), such mixing can significantly *reduce* the effective X-ray emission. While there have been some numerical simulations of the complex structure that arises from such instabilities (e.g., Walder & Folini 1998), there unfortunately does not yet appear to be any detailed study of how this can affect the net X-ray emission.

To characterize the potential mixing effect on the L_x-L_{bol} scaling, let us make the plausible *ansatz* that the reduction should, for shocks in the radiative limit $\ell/r \ll 1$, scale as some power of the cooling length ratio, ℓ/r. To ensure that the mixing effect goes away in the adiabatic limit, we can (much as in eqn. 1) assume a simple 'bridging law' scaling for a "mixing reduction factor" for X-rays,

$$f_{xm} = \frac{1}{(1 + r/\ell)^m} \, , \tag{6}$$

where the mixing exponent $m > 0$. To account for mixing within this model, we thus simply multiply the X-ray emissivity η_x in eqn. (1) by this mixing factor f_{xm}.

As a specific, simple model, let us next also assume that, beyond some onset radius R_o, the X-ray heating fraction declines as power-law in radius, $f_q(r) = f_{qo}(R_o/r)^q$. Neglecting absorption, the X-ray luminosity can then be obtained from spherical volume integration of this X-ray emission,

$$L_x = 4\pi C \int_{R_o}^{\infty} f_{xm} f_v \rho^2 r^2 dr = 4\pi C_q \left(\frac{\dot{M}}{4\pi V_\infty} \right)^2 \int_{R_o}^{\infty} \frac{dr}{r^q \, (rw + R_a)^{1+m} \, (rw)^{1-m}} \, , \tag{7}$$

where $C_q \equiv C f_{qo} R_o^q$, and $w(r) \equiv V(r)/V_\infty$ is the scaled wind speed. For the standard $\beta = 1$ velocity law, we have $rw = r - R_*$, which even for general values of q and m allows analytic integration of (7) in terms of the Appell Hypergeometric function. As a specific example, for shock heating that declines with inverse radius ($q = 1$), direct numerical evaluation shows that the total X-ray luminosity is well approximated by a simple bridging law between the radiative and adiabatic limits,

$$L_x \approx 4\pi C_q \left(\frac{\dot{M}}{4\pi V_\infty R_*} \right)^2 \left\{ \frac{1}{R_o/R_* - 1} + \ln(1 - R_*/R_o) \right\} \left[\frac{R_o}{R_o + R_a/(1+m)} \right]^{1+m} \tag{8}$$

$$\propto \left(\frac{\dot{M}}{V_\infty} \right)^2 \quad ; \quad R_a \ll R_o \tag{9}$$

$$\propto \left(\frac{\dot{M}}{V_\infty} \right)^{1-m} \quad ; \quad R_a \gg R_o \, , \tag{10}$$

where the curly bracket term follows from straightforward integration of (7) for $R_a \to 0$, in which case the square bracket term just becomes unity; the latter scalings follow from limit evaluations of this square bracket, using the definition of R_a in eqn. (5). The transition $R_a \approx R_o$ marks a kind of "sweet spot" for conversion of shock energy into X-ray emission; for lower density winds ($R_a < R_o$) much of that energy is lost to adiabatic expansion, while for higher density winds ($R_a > R_o$), it is lost to thin-shell mixing.

In very dense winds with optically thick X-ray emission and so $R_1 > R_o$, one can approximately account for the associated wind absorption through an "exospheric" approach (OC99) in which R_1 simply replaces R_o as the lower bound for the integral in (7), and thus also in (8). Since $R_a/R_1 = \kappa_c/\kappa_{bf} \approx 8 \gg 1$, the square bracket term just becomes a fixed constant, independent of $\dot{M}$. Moreover, expansion of the curly bracket term now also makes the overall L_x scaling *independent* of $\dot{M}$ for this $f_q \sim 1/r$ ($q = 1$) emission case in the dense wind limit, $R_a > R_1 \gg R_o$.

4. Summary and Future Work

The key result of this paper is that, in the common case of moderately dense winds with radiative shocks ($R_a > R_o$), thin-shell mixing can lead to a *sub-linear* scaling of the X-ray luminosity with the mass-loss rate, $L_x \sim (\dot{M}/V_\infty)^{1-m}$. For a quite reasonable mixing exponent value $m \approx 1 - \alpha \approx 0.4$, this then gives roughly the *linear* L_x-L_{bol} law that is empirically observed for O-star X-rays.

However we note that a similar mixing analysis could also be applied to model X-ray emission from colliding wind binaries, and their L_x scaling with orbital separation. Wide binaries with adiabatic shocks should still follow the usual inverse distance scaling, as directly confirmed by observations of multi-year-period elliptical systems like WR140 and η Carianae (see review by Corcoran). But in close, short (day to week) period binaries with radiative shocks, mixing could reduce and limit the effective X-ray emission from the wind collision, and thus help explain why such systems often hardly exceed the $L_x \approx 10^{-7} L_{bol}$ scaling found for single stars (see review by Gagné).

Finally, in addition to exploring such effects in colliding wind binaries, an overriding priority for future work should be to carry out detailed simulations of the general effect of thin-shell mixing on X-ray emission, and specifically to examine the validity of this mixing-exponent *ansatz* for modeling the resulting scalings for X-ray luminosity.

Acknowledgments. This work was carried out with support from NASA ATP grant NNX11AC40G.

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